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Filtration Rates and Impurities In Raw Sugar Crystals

Hugo P. Kortschak[1]

The rate at which sugar solutions can be filtered is of great importance to sugar refineries. It was first noted (63) about 1910 that some sugars filter very much more slowly than others, and since that time much work has been done to determine what impurities in the raw sugar cause these occasional low filtration rates. Since much of this work is little known (12), a brief summary may be useful.

At first, slow filtration was thought to be due to high viscosity (8, 48, 45), and although it was soon found that variations in viscosity are relatively small (34, 9), the concept lingered on as late as 1925 (2). It is insoluble material in the raw sugar which retards filtration (43, 1, 49, 34, 13, 18, 50, 57, 45, 28). King (31) doubted this, due to a misinterpretation of some of his experimental results.

The solid material is not only in the film of molasses surrounding each sugar crystal (24, 52) but, as first noted by Hadfield (18), is inside the crystal itself (36, 21, 24, 38, 9, 10, 16). It has often been called "colloids" (22, 39, 53, 52, 59, 51) or "gums" (48, 34, 18, 29, 6, 52, 59), although the greatest effect is due to particles too large to be considered truly colloidal (1, 18, 50, 57, 36, 45, 37, 38, 9).

As to the chemical composition of the material, some think that it is cane wax (8, 17, 20, 61) and the prevalence of this view was furthered by Bardorf's (3) analyses showing traces of wax in refined products. However, it has been shown (28) that some low filtration rate sugars are not improved by the removal of wax. Starch has also been blamed (11, 17).

Although it has not been disproved that wax, or starch, may sometimes be the sole cause of poor filterability, it appears to be generally accepted that all kinds of material suspended in the cane juice may be included in the crystal and may cause low filtration rates (43, 1, 49, 34, 13, 18, 50, 57, 45, 28). The influence, in particular, of cane trash (40, 53, 52), soil (12), micro-organisms (1, 62, 53) or weeds (30) has been emphasized.

The question as to why insoluble materials are sometimes present in the raw sugar crystal has also been investigated. Some tests seemed to show that hot or excessive maceration water had a bad effect (38, 51, 61), but one very thorough factory-scale test (19) failed to show that this had any influence. Poor boiling methods can decrease filtration rates by building up the concentration of suspended

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solids in the first and second molasses (60, 54) or by causing inclusions of molasses in the sugar (10, 52).

All who have studied the problem find that poor clarification causes low filtration rates (43, 27, 56, 35, 33). The use of phosphate (55, 47, 40, 15, 58) or other means (32, 6, 20, 61, 5) to improve clarification will often result in the production of raw sugar which no longer causes difficulty in the refinery. Without efficient clarification of the cane juice, it is not possible to produce high filtration rate sugar.

The present investigation was divided into two parts. The first was a study of the Elliott filtration rate test. In the second, solid material was removed from sugar samples, to correlate amount and kind of impurity with filtration behavior.

FILTRATION OF SUGARS IN THE ELLIOTT TEST

It has been a general impression that, with sugars of low filtration rate, the bulk of the amount filtered appeared in the first few minutes with little or no flow during the remainder of the 30 minutes of the Elliott test (7). The following table shows the percentage of the total volume filtered in the first and last five minutes of the test, respectively, for total volumes varying from 42 to 424 ml. (These figures are corrected for the 13 ml. filtered before filtrate runs into the receiver). Data for the 5 samples of lowest filtration rate are given individually, then averages for groups of increasing filtration rate.

All filtration rates reported were measured with a small filter leaf, having approximately one-eighth the area of the standard apparatus. Determinations on several sugar samples proved that the results were strictly proportional to those obtained with the standard, larger size, filter.

TABLE I
FILTRATION CHARACTERISTICS OF RAW SUGARS

Total Volume (cc.)	Filt. Rate	No. of Samples	% Volume first 5 mins.	% Volume last 5 mins.
42	9	1	42.9	8.8
68	17	1	35.3	10.3
71	18	1	32.4	11.3
93	25	1	36.6	9.7
96	26	1	36.5	9.4
42– 99	9– 26	5	36.7	10.2
100–199	27– 59	34	36.7	9.7
200–299	60– 90	29	36.5	9.7
300–399	91–121	11	35.6	9.9
400–424	122–129	2	34.7	9.2

It can be seen that the behavior of the solutions is similar over this wide filtration rate range. In all cases about 10% of the total volume is collected in the last 5 minutes, showing that the general impression mentioned above is incorrect.

If it is assumed that during filtration the flow rate is always inversely proportional to the thickness of the filter cake, and that this is proportional to the amount of liquid which has been filtered, then, if V = volume and t = time,

$$\frac{dV}{dt} = \frac{1}{KV} \quad \text{or} \quad \frac{dt}{dV} = KV$$

and

$$\frac{d^2T}{dV^2} = K$$

This means that the difference in the time required for the filtration of successive equal volumes should be constant. This has been found to be true. The time difference, when the filtered volume increments are 50 cc. has been called D.

TABLE II
RELATIONSHIP OF VOLUME FILTERED AND TIME

Volume filtered (cc.)	Time required (secs.) for 50 cc.	D
0– 50	370	–
50–100	740	370
100–150	1090	350
150–200	1460	370

The logarithm of the D values has the useful property of enabling one to predict the filtration rate of a mixture of sugars, when the rate for each sugar is known. In the following example, two sugars whose filtration rates were 100 and 17 were mixed in varying proportions and the filtration rates and D values determined.

TABLE III
INTERPOLATION OF FILTRATION RATES OF MIXTURES OF RAW SUGARS

% 17 F. R. Sugar	0	10	30	70	100
Filt. Rate	100	85	61	32	17
D	66	90	153	505	1400
Log D	1.82	1.95	2.18	2.70	3.15
Log D calc.	–	1.95	2.22	2.75	–

(D values can be calculated from filtration rates, but the formula is complicated. For practical purposes they can best be read off from a graph.)

SOLID IMPURITIES AND FILTRATION RATES

Methods

At the time these experiments were started, it was difficult to find any large samples of low filtration rate sugars. Samples I to VII were taken directly from the centrifugals at Hakalau Plantation Company; molasses samples were taken from the same centrifugal at the same time as the correspondingly numbered sugar. The two sugars of very low filtration rate, VIII and IX, were composite samples sent in by plantations and only a limited amount of these was available.

The raw sugar was washed, according to the standard procedure of the Sugar Technology Department, with raw sugar syrup, white sugar syrup, and isopropyl alcohol saturated with sugar. It was air dried. The washed sugar solution was made up by dissolving in an equal weight of distilled water. Solid impurities of successively smaller size were then removed by the following procedures, filtration rates being determined after each step:

TABLE IV

QUANTITY OF INSOLUBLE MATERIAL IN RAW SUGARS
(Per cent of sugar and molasses)

Sample	I	II	III	IV	V	VI	VII	VIII	IX	III Mol.	IV Mol.	V Mol.	VI Mol.
Screened	.025	.020	.015	.012	.026	.026	.055	.010	.008	.000	.000	.000	.000
H Filtered	.014	.007	.0039	.0017	.0014	.0026	.007	.011	.012	.089	.144	.039	.026
Centrifuged (after H filtered)	.068	.024	.025	.032	.025	.031	.029	.111	.062	.543	.817	1.114	.484
Alcohol Precipitated	.363	.285	.073	.167	.135	.154	.145	.311	.623	6.95	8.00	4.10	6.78
Alcohol Precipitated after Filtration	.172	.135	.045	.039	.083	.087	...	.222	.059	2.09	5.00	2.50	1.75

1. The washed sugar, dissolved in an equal weight of distilled water, was allowed to flow through a 200 mesh screen.

2. The screened solution was filtered with vacuum through a sintered stainless steel filter ("H" grade) with a rated pore size 5 microns.

3. The "H" filtered solution was diluted with an equal weight of water and centrifuged in 250 cc. bottles for 2 hours at 2000 r.p.m. (International Centrifuge, size 2). The decanted liquid was evaporated under vacuum to the original density.

4. The centrifuged solution was filtered as in the Elliott test.

5. To another portion of the centrifuged solution was added sufficient 95% alcohol to bring the solvent to 50% alcohol by weight. After standing over night, this was centrifuged for 1 hour. The liquid was evaporated nearly to dryness, then diluted to the original density.

6. The filtered solution (4) was alcohol precipitated as in (5).

Molasses samples were diluted with an equal weight of water and fractionated in the same way as the sugar solutions.

All precipitates were collected on sintered glass filters and washed with 50% alcohol. They were dried 2 hours at 110° C. After weighing, the precipitate, or about half a gram when a large amount was obtained, was boiled with 25 cc. toluene, filtered hot, and 25 cc. petroleum ether run through. The solvents were evaporated and the residue reported as "wax."

Filtration Rates and Particle Size

Table V shows that it is the material removed by centrifuging which has the most important effect on filtration rates. Centrifuging improves the rates of the poorer sugars to normal values, while leaving those of the better samples unchanged.

TABLE V
FILTRATION RATES OF SUGARS

Sample	I	II	III	IV	V	VI	VII	VIII	IX
Washed	43	56	72	49	61	48	49	..	16
Screened	43	56	68	51	64	51	51	..	..
H Filtered	44	76	72	50	65	48	55	9	18
Centrifuged (after H filtered)	62	70	70	59	73	58	69	42	51
Alcohol Precipitated	105	78	86	110	129	..	128	..	..
Alcohol Precipitated after Filtration	100	91	99	106	101	70	100	90	86

Many unsuccessful attempts were made to prove that the isolated material will lower filtration rates of sugar solutions. As previously found by King (31), adding the insoluble matter isolated from raw sugar to a solution of white sugar has only a small effect on the filtration rate. It was finally discovered that when such solids are added to a filtered solution of raw sugar, the filtration rates are reduced.

Table VI gives the filtration rates found when the material separated from two sugars by filtration through the sintered metal filter (H) was added to white and to filtered raw sugar solutions.

TABLE VI
EFFECT OF RETURNING H FILTERED SOLIDS TO SOLUTION

Screened	H Filtered	Filtered +H ppt.	White	White+ H ppt.
28	40	28	99	95
41	44	41	99	103

When the precipitate is added to the solution of raw sugar from which it has been removed, the filtration rate drops to the "screened" value; the removed material has been resuspended. When a solution of white sugar is used, the filtration rate remains high.

Some non-sucrose material, which acts to maintain the impurities in suspension, must be present in the raw sugar. Most probably, the concentration of inorganic, ionized substances is important, but unfortunately it was not possible to investigate this further.

Effect of Amount of Suspended Solids in the Molasses

An important point in the study of filtration rates is to determine how much of the solid material present in the massecuite is contained in the sugar crystals. It is believed that boiling methods can influence the amount of solid matter which becomes part of the raw sugar; unfortunately, as all these molasses samples came from one factory, this cannot be tested from the data. However, as the corresponding

samples of raw sugar varied from 48 to 72 in filtration rate, some information can be obtained.

The simplest picture would be that the solids were distributed evenly throughout the volume of the massecuite. In this case, the sugar and molasses samples would contain nearly equal amounts of impurities. Table VII shows that this is not the case, as the amount in the sugar never approached that in the molasses.

TABLE VII
AMOUNT OF TOTAL SOLIDS WHICH ENTERS CRYSTAL
Solids in Sugar as % of Solids in Molasses

Sample	III	IV	V	VI
H Filtered	4.4	1.2	3.6	10.0
Centrifuged (after H filtered)	4.7	3.9	2.2	6.4
Alcohol Precipitated	1.1	2.1	3.3	2.3
Alcohol Precipitated after Filtration	2.2	0.8	3.3	5.0

Another simple mechanism would be the inclusion of small amounts of molasses within the crystal. Here the relative amounts of different kinds of impurities would be the same in both sugar and molasses. Although it is most probable that some occlusion of this kind does take place, the relative amounts are not the same except for sample No. V, showing that this is probably not the main mechanism.

Looking at each individual class of impurity, it can be seen that neither a constant amount nor a constant percentage of the material present becomes a part of the sugar. From Table VIII, in which the ratio, solids in sugar: solids in molasses is compared with the amount in the molasses, a definite relationship can readily be seen. The larger the amount of impurity present, the smaller the percentage which enters the crystal.

Practically, this non-linear relationship is extremely fortunate. It seems that when solid impurities in the molasses are present in unusually large quantity, the amount occluded in the sugar may be greater than usual, but not in proportion to the excessive amount in the molasses.

As far as can be seen, there are no large deviations from this regular behavior, indicating that the impurities in the different samples are similar in this respect.

TABLE VIII
RELATIONSHIP BETWEEN PER CENT OF INSOLUBLE MATERIAL ENTERING SUGAR AND AMOUNT PRESENT IN MOLASSES

H Filtered		Centrifuged after H Filtered		Alcohol Precipitated	
% of Mol.	% in Sugar	% of Mol.	% in Sugar	% of Mol.	% in Sugar
.029	10.0	.424	6.4	4.10	3.3
.039	3.6	.534	4.7	6.78	2.3
.089	4.4	.817	3.9	6.95	1.1
.144	1.2	1.114	2.2	8.0	2.1

Alcohol Precipitated after Filtration	
% of Mol.	% in Sugar
1.75	5.0
2.09	2.2
2.50	3.3
5.0	0.8

Analyses of Impurities

Analyses of the solid material separated from the sugar samples were made for two purposes:

(1) to compare the composition of solids from sugars of low filtration rate with those from better sugars.

(2) to compare material separated from sugars with the corresponding material from molasses.

In order to reduce the amount of analytical work required, only those analyses were made which would serve one of these two purposes. In several cases, the amount of material isolated was too small to make possible all the analyses which would have been desirable.

Analyses made were wax (toluene soluble), carbohydrate (by T. Tanimoto), nitrogen (by D. Takahashi), total carbonate ash (by T. Jones) and chlorophyll (by C. E. Hartt). In nearly all cases the sum of these was over 70% of the total weight of the precipitate, indicating that there is no other major component.

Chlorophyll

Due to the destruction of chlorophyll during and after isolation of the precipitates, the quantitative values (Table IX) are only minimal. It is evident that much of the solid material in the sugar comes from leaves.

TABLE IX

Precipitate	% Chlorophyll
IV Cent.	.027
V Cent.	.002
V Mol. Cent.	.021
VI Mol. Alc.	.011

TABLE X
COMPOSITION OF CENTRIFUGED PRECIPITATES

	III	IV	V	VI	VIII	IX	III Mol.	IV Mol.	V	VI Mol.
Wax	7.3	5.1	2.1	..	10.7	12.6	5.3	2.9	3.6	6.1
Carbohydrate	12.6	..	6.3	6.6	9.7	11.5	17.2	..	15.4	11.1
Protein†	15.1	..	13.2	..	24.2	20.8	15.6	..	13.7	..
Ash	42.5	..	51.6	..	13.7	18.0	34.6	..	41.5	41.9

† N×6.25

TABLE XI
COMPOSITION OF ALCOHOL PRECIPITATES

	III	IV	V	VI	VIII	IX	III Mol.	IV Mol.	V Mol.	VI Mol.
Wax	3.40	4.15	1.77	0.7	3.04	2.65	2.07	2.66	4.5	3.49
Carbohydrate	62.8	55.5	52.9	46.7	33.3	39.4	48.2	19.1	26.1	15.7
Protein	12.7	9.6	9.6	10.4	18.3	7.4	5.4	9.4	5.4	7.9
Ash	12.7	12.1	11.3	16.7	11.2	4.8	18.2	30.0	21.6	34.9

TABLE XII
COMPOSITION OF H-FILTERED PRECIPITATES

	III	III Mol.	IV	IV Mol.	V	V Mol.	VI	VI Mol.
Wax	0	0.78	5.4	2.1	0	1.0	0	2.1
Carbohydrate	27.2	9.8	19.3	9.4	29.7	..	..	..
Protein	..	11.6	..	12.1	..	7.4	..	..
Ash	35.9	50.0	..	50.9	..	..	..	..

TABLE XIII
COMPOSITION OF FILTERED ALCOHOL PRECIPITATES

	III	III Mol.	IV	IV Mol.	V	V Mol.	VI	VI Mol.
Wax	2.5	0.8	0.3	2.7	2.7	4.7	..	..
Carbohydrate	..	..	13.7	8.2	70.7	11.8	..	..
Protein	..	..	15.7	6.9	1.9	6.7	..	..
Ash	..	..	42.1	51.0	8.7	44.6	..	..

The large proportion of organic material in all fractions (Tables X–XIII) shows that the impurities do not come from the soil. Since the cane came from several different areas, and no large amounts of weeds were observed to be entering the mill at the time, the impurities must stem from the cane plant itself. The presence of chlorophyll in all the samples examined for this compound indicates that at least part comes from the leaves.

There is no indication that any particular compound or class of compounds has more to do with filtration difficulties than any other, although impurities from poorly filtering sugars tend to have a lower ash content.

The similarity of the analyses of these materials with those of cane juices themselves, and with extracts of leaves, makes it most probable that the solids are already present in the cane plant.

Comparison Between Material from Sugars of Low and Normal Filtration Rates

Centrifuged precipitate. Comparing the low filtration rate sugars VIII and IX with more satisfactory samples (Table X), a difference in composition is evident. Protein and wax are higher, ash lower, for the poor sugars. If, however, we examine the organic portion of the precipitate only (Table XIV), no significant differences are evident. It seems that the main difference in composition is the lower percentage of ash in the samples from sugars of low filtration rate.

TABLE XIV
COMPOSITION OF ORGANIC PORTION OF CENT. PRECIPITATES

	III	V	VIII	IX
Filtration Rate	72	61	9	16
Wax	21	10	24	28
Carbohydrate	36	29	22	26
Protein	43	61	54	46

An obvious possibility is that the higher percentage of organic matter, with consequent lower density, caused poor settling during clarification. This, in turn, could be due to low phosphate in the juice.

Alcohol precipitate. Examination of the alcohol precipitates (Table XI) does not

reveal any very definite difference between low and high filtration rate sugars, though carbohydrates and ash are somewhat lower for these. Note that the extremely large alcohol precipitate of IX contains a very low percentage of ash.

For the other types of precipitates, it was not possible to obtain sufficient analyses to draw any conclusions.

Summarizing, the solid material in sugars of extremely low filtration rate is similar in composition to that in better sugars, except that the ash is lower.

Corresponding Precipitates from Sugar and Molasses

When we compare the fractions isolated from sugar with those from the corresponding molasses samples, it is apparent that the compositions, though generally similar, are not identical. The question arises whether these differences are real or fortuitous.

It is most improbable that errors in sampling or analysis could give rise to variations as large as those found. There is no doubt, however, that the different fractions obtained are not strictly comparable.

Although this can hardly account for the large differences in per cent carbohydrate and ash found in the alcohol precipitates, there must also have been some precipitation of water soluble materials from the molasses. It was hoped to approximate the amount of solid matter precipitated by alcohol by subtracting the amount precipitated from the filtered solutions, but the results give no coherent picture.

CONCLUSIONS

1. Low filtration rates of raw sugars are due mainly to inclusions of solid particles whose dimensions are of the order of 1 micron.
2. Any solid material present in the syrup can be mechanically included in the sugar crystal.
3. There is no evidence that any one substance, or class of substances, is more apt than any other to be included as a solid impurity in the sugar crystal.
4. At least a large part of the solid material in the raw sugar has its origin in the leaves of the cane plant.

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Getting More Information for Less Money Through Factorial Design in Experiments

Ralph J. Borden[1]

Field experiments on plantations, if designed to produce broad and accurate results, will compensate for the time and trouble involved by the value of the information produced. Since it is undeniably costly to conduct experimental programs, it is essential that the plans for the full complement of objectives be made as carefully as possible, so that the harvested tests will produce the maximum amount of information in the most effective and economical manner.

To make field experiments more efficient, the wider use of factorial plans is recommended. A factorial plan is one which makes possible a simultaneous study of two or more factors. The illustrations which follow will show how such a plan would have enabled several existing single-factor tests to furnish more information at no increase in cost. In other words, because the plans were not factorial, the potentialities were not fully realized.

1. In Field 22, Experiment No. 83V devotes 24 plots to the testing of four varieties in six replications. In the same field, Experiment No. 87 uses 14 plots to test two amounts of potash in seven replications. Hence, these two separate tests, occupying a total of 38 plots, will, at harvest, give average yields for comparisons from six plots of each variety, and from seven plots of each potash treatment.

If these two objectives had been combined into a single 4 x 2 Variety x Potash factorial plan with its eight combined-treatments, and if these had been replicated four times, a total of only 32 plots, instead of 38, would have been required. The average yields would have come from eight instead of from six plots for each variety, and from 16 instead of from only seven plots for each potash level. In addition, there would have been an opportunity to identify any possible interaction between varieties and potash, an opportunity not available when the two tests are made separately. Furthermore, the main treatment effects from varieties and from potash, if there were no proved interaction, as well as from their interaction, if it were significant, would be tested against more degrees of freedom for error. Thus the factorial experiment as a whole would be more sensitive to the measurement of small differences

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between its treatments. The analysis of variance for the two separate tests and for the factorial plan would be as follows:

For the Variety test. (24 plots)		For the Potash test. (14 plots)		For the Factorial V x AK test. (32 plots)	
Source	**d.f.**	**Source**	**d.f.**	**Source**	**d.f.**
Blocks	5	Blocks	6	Blocks	3
Varieties	3	Potash	1	Varieties	3
Error	15	Error	6	Potash	1
				Var. x Potash	3
Total	23	Total	13	Error	21
				Total	31

With only six degrees of freedom for error in the potash test, there is no very reliable error term with which to measure the significance of the treatment differences. In the absence of interaction, the 21 degrees of freedom for error in the factorial will provide a much more reliable estimate of error. This error term will also provide a good measure of an interaction, if one is present.

2. Experiment No. 113I includes four irrigation treatments replicated six times on variety 38–2915 in Field 22, and the same four treatments replicated four times on variety 37–1933 in Field 81. This installation calls for two separate statistical analyses to determine the significance of each irrigation treatment: one for the average difference from six plots of each treatment on variety 38–2915; the other for the average difference from only four plots of each treatment on variety 37–1933. No valid comparison of the two varieties is possible since field locations contribute differences, and no effect of interaction between treatments and varieties can be reliably identified. Finally, with only nine degrees of freedom for error in the 37–1933 test area, the measurement of the irrigation treatment effects on this variety is not very sensitive.

If these same 40 plots had been used for a well-planned 4 x 2 Irrigation x Variety factorial with the eight combined-treatments replicated five times, averages for comparisons would have been possible from ten plots instead of from six or four of each irrigation treatment, and also from 20 plots of each variety. It is likely that any possible interaction between treatments and varieties could have been found, and, with the much greater number of degrees of freedom for error than was provided by either of the separate tests, the measurement of significance of all known effects would have been more reliable.

The analysis of variance for these plans would be as follows:

For Variety 38-2915 only (24 plots)		For Variety 37-1933 only (16 plots)		For the Factorial Tr'mt. x Var. test. (40 plots)	
Source	**d.f.**	**Source**	**d.f.**	**Source**	**d.f.**
Blocks	5	Blocks	3	Locations	1
Treatments	3	Treatments	3	Blocks in Loc.	3
Error	15	Error	9	Treatments	3
				Varieties	1
Total	23	Total	15	Tr'mt. x Var.	3
				Error	28
				Total	39

3. In Experiment No. 29 in Field 50, a total of 20 plots are devoted to testing 10 replicates of two varieties. The analysis of variance for this test will be:

Source	d.f.
Blocks	9
Variety	1
Error	9
Total	19

This test could just as easily have tested another factor (which may be called "Y")* at two levels or differences, thus making it a 2 x 2 Variety x "Y" factorial, with five replicates. The analysis would then have been:

Source	d.f.
Blocks	4
Variety	1
Factor "Y"	1
Var. x Y	1
Error	12
Total	19

The factorial plan would still give 10 plots of each variety for the determination of their average yields, and also another 10 plots to average for each level of the added factor "Y", as well as a fair measure of their interaction, and a few more degrees of freedom for error against which to measure the treatment effects. Thus, a combined test with its much wider scope could have been handled at no extra cost.

4. In Experiment No. 1014 in Field 23.2, the 24 plots being used for testing eight replicates of three varieties would be more efficiently used for a 3 x 2 Variety x "Y" factorial plan with four complete replicates. The comparative analyses would be these:

As installed:

Source	d.f.
Blocks	7
Varieties	2
Error	14
Total	23

As a 3 x 2 Factorial:

Source	d.f.
Blocks	3
Varieties	2
Factor Y	1
Var. x Y	2
Error	15
Total	23

Thus, the additional information about Factor "Y" would be obtained without either the sacrifice of any reliability for the average yields of the varieties, or any loss of degrees of freedom for testing the variety effects.

5. In Experiment No. 84 in Field 90, the 32 plots used for testing eight replicates of four soil treatments could be made to give added information about some other factor "Y", without reducing the reliability of the average yields from the soil treatments, or the precision, that is, degrees of freedom, for measuring these treatment effects. A 4 x 2 Soil Treatment x Factor "Y" factorial with four replicates would give additional information as this analysis will show:

*This Factor "Y" could be one of many, e.g., amounts or time of application of N, P, or K; differences in width of row, or in ripening technique, or age of harvest; etc.

As Installed:

Source	d.f.
Blocks	7
Soil Tr'mts.	3
Error	21
Total	31

As a 4 x 2 Factorial:

Source	d.f.
Blocks	3
Soil Tr'mts.	3
Factor Y	1
S.T. x Y	3
Error	21
Total	31

6. In Experiment No. 182 in Field H5, there are 20 plots being used to test plant crop yields against ratoons with 10 replications. It would have been a simple matter to introduce another factor into this test, nitrogen at two levels, for instance, and to get an answer to another question that has been asked by many and answered by none: "Do ratoon crops need more nitrogen than plant crops?" Had such a 2 x 2 Crop x Nitrogen factorial been made on these same 20 plots, it would have provided the equivalent 10 replicates for the average of each crop yield as well as 10 replicates for each amount of nitrogen, but, what is more important, from the significance found for the Crops x N interaction, it would have also answered the above question. For this example, the analysis of variance would be:

As Installed:

Source	d.f.
Blocks	9
Crops	1
Error	9
Total	19

As a 2 x 2 Factorial:

Source	d.f.
Blocks	4
Crops	1
Nitrogen	1
Crops x N	1
Error	12
Total	19

It should be quite clear from these examples that factorial plans have some distinct advantages over the single-factor tests, and thereby afford plantation testing programs a real opportunity to obtain more information per dollar expended.

Available Phosphorus in Hawaiian Soil Profiles

A. S. Ayres and H. H. Hagihara[1]

Sampling of soils for determination of available phosphorus is generally restricted to the depth of tillage or to the surface foot of soil. Deeper sampling is not ordinarily feasible. In the case of a deep-rooted crop, such as sugar cane, the zone from which the plant obtains its supply of phosphorus is not always completely represented. Therefore, in evaluating analyses of soils which support deep-rooted crops, it is helpful to understand something of the relationship of the levels of phosphorus in the unsampled portions to the levels in the sampled portions of the root zone. The work which has been done towards defining that relationship is presented in this paper.

Studies of the vertical distribution of available phosphorus were reviewed in 1940 by Pearson, Spry and Pierre (8). Results of more recent studies have been summarized by Allaway and Rhoades (1). Most of the work indicates increasing supplies of available phosphorus with increasing depth. With some soils, phosphorus decreases to a minimum in the B, or in the lower part of the A horizon, and reaches a maximum in the C. Heavy fertilization of soils naturally deficient in phosphorus has frequently resulted in marked differentiations in amounts of phosphorus in surface and subsoil layers.

DESCRIPTION OF SOILS

The soils used in this study were the same as those examined in earlier studies of the distribution of exchangeable potassium in the soil profile (4,5). They represent 15 of the soil families upon which sugar cane is grown. All originated either on Oahu or on Hawaii. They include the extremes in phosphate fixing ability found in the Hawaiian Islands. The location of each soil, the soil group, family name, elevation and rainfall data are shown in the Appendix.

METHOD OF SAMPLING

Phosphate fertilizer is generally applied in the furrow when the seed is planted. With ratoon cane, phosphate is either applied to the soil surface, generally in the cane line, or it is drilled by means of a subsoiler into the soil near the cane line. It was felt, therefore, that soil samples would be least affected by recent fertilization if they were taken midway between the rows of cane.

A trench five to six feet long and two feet deep was dug in the center of the interrow. The profile thus exposed was sampled by slicing a thin layer of soil from

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one face of the trench in six-inch increments. Sampling was extended to a depth of four feet by a series of auger borings in the bottom of the trench. Here also samples were taken in increments of six inches.

In a few instances, where shallow soils were encountered, the depth of sampling was determined by the depth of soil. The depths to which the soils were sampled are indicated in the Appendix. A total of 31 profiles were studied, including those of two forested soils and one grassland soil, which were adjacent to sugar cane lands.

METHOD OF ANALYSIS

Most of the phosphorus in soils is present in forms which are essentially unavailable to plants. Much of it exists as insoluble compounds of hydrated iron and aluminum oxides. In calcareous soils, insoluble calcium and magnesium phosphates are present. The silicate clay fractions of many soils retain phosphorus in exchangeable form, which, in certain pH ranges, is only difficultly available. Approximately a third of the total soil phosphorus exists in organic combination. These organic forms are very resistant to attack by soil micro-organisms and so are correspondingly unavailable to plants.

It is apparent from the foregoing discussion that knowledge of the total amount of phosphorus in the soil would be of little help to the agriculturist in the formulation of a fertilizer program. It becomes necessary, therefore, to analyze the soil with the specific purpose of obtaining a measure of the very small fraction of the total phosphorus which is utilizable by the crop. This may be accomplished either chemically, by means of certain extractants, or biologically, as in the Aspergillus niger method and in pot studies. If a chemical test is made, it is desirable to employ an extractant which will remove from the soil an amount of phosphorus which will approximate that available to the immediate crop.

The procedure employed in the present study was developed expressly for the purpose. It consists of a modification of the widely used Truog technique. In its original form (10) this method utilizes as the extractant a .002 N solution of sulfuric acid, buffered with ammonium sulfate to pH 3.0. Acid of this strength is well suited to the estimation of available phosphorus in many soils. For some of the more highly weathered lateritic soils of Hawaii, however, it is too weak. The authors have found it advisable to increase the concentration of the acid to .02 N. Table 1 shows how increasing the strength of sulfuric acid through the range from .002 N to .15 N affects the solubility of soil phosphorus.

Another departure from the Truog procedure consists in the removal of the considerable quantities of organic matter which appear in some of the soil extracts

TABLE 1

STRENGTH OF ACID IN RELATION TO SOLUBILITY OF SOIL PHOSPHORUS

Soil No.	Location	Great Soil Group	Phosphorus in p.p.m. of Soil		
			.002 N H_2SO_4	.02 N H_2SO_4	.15 N H_2SO_4
44–30	Paauilo	Humic Latosol	2	[illegible]	[illegible]
44–8	Poamoho	Low Humic Latosol	4	[illegible]	[illegible]
44–[illegible]	Olaa	Hydrol Humic Latosol	4	[illegible]	[illegible]
44–15	Kilauea	Humic Ferruginous Latosol	5	[illegible]	[illegible]
44–18	Puhi	Low Humic Latosol	25	[illegible]	[illegible]
44–[illegible]	Waikiki	Alluvium	276	[illegible]	[illegible]
44–3	Makiki	Low Humic Latosol	441	[illegible]	[illegible]

and which may interfere with the subsequent determination of phosphorus. This is accomplished by the addition of a small amount of activated carbon[2] to the soil-extractant mixture prior to shaking.

The relative amounts of soil and extracting solution employed in the determination of phosphorus are nearly as important with many Hawaiian soils as the strength of the acid, when results are to be expressed, as is customary, on the basis of the weight of soil used. This is evident in Table 2. Here are shown the quantities of phosphorus dissolved per unit weight of soil when, keeping the volume of the extractant constant at 200 ml., weights of soil are increased from 2 to 20 gm. In the present modification of the Truog procedure, the ratio of soil to extractant is increased from 1:200 to 1:100.

With respect to the soil-extractant ratio, method of color development, and precautions against interference by ferric, arsenate and nitrate ions, the method employed follows the modified Truog procedure of Peech et al (9).

TABLE 2

EFFECT OF VARYING THE SOIL: EXTRACTANT (.02 N H_2SO_4) RATIO ON THE QUANTITY OF PHOSPHORUS EXTRACTED PER UNIT WEIGHT OF SOIL

Soil No.	Location	Great Soil Group	Wt. of Soil	Vol. of Extractant	Soil/Extractant	P Extracted	P extracted per unit wt. of soil	Final pH of Extractant*
			gm.	ml.		μg**	p.p.m.	
44–7	Waialua	Low Humic Latosol	2	200	1:100	100	50	2.1
			5	"	1:40	140	28	2.2
			10	"	1:20	146	15	2.5
			15	"	1:13	121	8	2.7
			20	"	1:10	90	5	3.0
44–17	Lihue	Humic Ferruginous Latosol	2	200	1:100	28	14	2.1
			5	"	1:40	31	6	2.2
			10	"	1:20	20	2	2.4
			15	"	1:13	16	1	2.6
			20	"	1:10	13	0.6	2.8
44–31	Honomu	Hydrol Humic Latosol	2	200	1:100	49	25	2.3
			5	"	1:40	33	7	2.7
			10	"	1:20	15	2	3.2
			15	"	1:13	9	0.6	3.5
			20	"	1:10	7	0.4	3.7

*Initial pH 2.0. ** Micrograms

CRITICAL LEVEL OF AVAILABLE SOIL PHOSPHORUS

It may prove helpful in considering the results of the study to have some concept of the amount of available soil phosphorus necessary to permit optimum growth of sugar cane. Such information is obtainable through correlation of soil analyses with response to phosphate fertilization in the field.

A study of this relationship by the authors is currently in progress. At the present time, it appears that the critical level of phosphorus for sugar cane is in the neighborhood of 20 parts of phosphorus per million parts of oven-dry soil, the tilled, or mixed layer alone being considered.[3] The value is purely empirical and has meaning only when phosphorus is determined by the procedure indicated or by a procedure giving equivalent results.

[2] DARCO G–60

[3] R. P. Humbert & A. S. Ayres, Soil Analysis for Available Phosphorus, Special Release #49, Experiment Station, H.S.P.A., Honolulu, Hawaii.

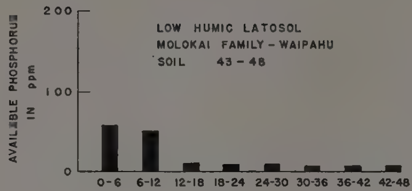
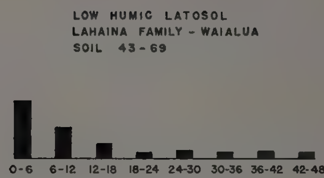


Figure 1



DEPTH IN INCHES

Figure 2

EXPERIMENTAL RESULTS

Distribution of available phosphorus in the profiles studied, together with corresponding pH values, is shown in the Appendix. The soils are listed and will be discussed in the order in which they will probably appear in the forthcoming report of the Hawaii soil survey. When two or more soils of a given family occur in the table, they are arranged in the order of increasing rainfall.

LOW HUMIC LATOSOLS

The first of the Low Humic Latosols to be considered is a virgin soil of the Molokai family found above the sugar cane lands at Ewa. This soil supports a sparse vegetation of grasses and cactus. Rainfall is seasonal and very low. Except for the surface six inches, the profile is only slightly acid.

Available phosphorus is uniformly distributed in this profile. The supply at a depth of four feet is essentially the same as in the surface foot. There is no surface accumulation of phosphorus.

The next three soils are members, respectively, of the Molokai, Lahaina and Wahiawa families of the same Group. Distribution of phosphorus in these soils, all of which are under cultivation, follows quite a different pattern. This may be seen by reference either to the Appendix or to Figures 1–3.

Here, when uniformity in the level of phosphorus exists, it is restricted to that portion of the profile which has been undisturbed by cultivation: that is, downward from a point 12 to 18 inches below the surface. The surface layer, presumably as a result of fertilization, is far richer in phosphorus than the lower portions of the profile. Phosphorus in these soils is above the critical level of 20 p.p.m.

Concentrations of phosphorus below the 18-inch level are much lower in these cultivated soils than in the virgin soil previously considered. This may indicate that the original supply of the element in the subsoil has been depleted by many years of cropping.

Consideration of the Low Humic Latosols is completed with reference to six profiles of Kohala family soils at the plantation of that name. Phosphorus is in good

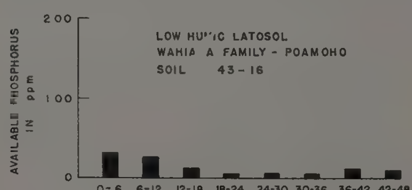
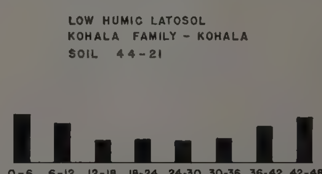


Figure 3



DEPTH IN INCHES

Figure 4

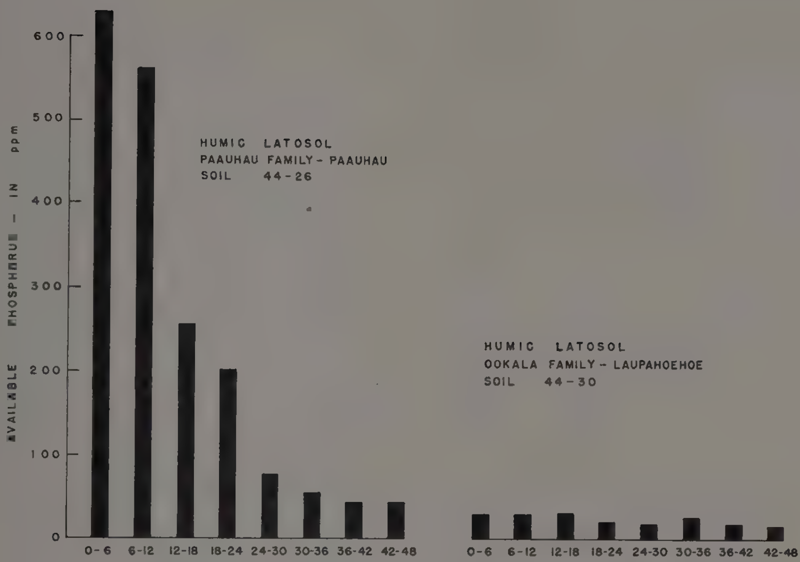


Figure 5 **Figure 6**

supply, well above the critical level in all of the soils. There is, however, considerable divergence in the distribution of phosphorus in the profile.

In two of the soils, No. 44–19 and 44–22, phosphorus is at much higher levels in the top six inches than in any other portion of the profile. In soil No. 44–23, on the other hand, phosphorus is lowest in the surface soil and increases to a maximum at the bottom of the profile. With others, the distribution is variable. Figure 4 represents a profile in which the supply of phosphorus first decreases with depth, and then increases.

HUMIC LATOSOLS

The Humic Latosols include all the cane lands of the Hamakua Coast, except those in the uppermost reaches. Two families of this group were studied.

The first is the Paauhau family, found at Paauhau, with an annual rainfall of 65 inches. The supply of phosphorus in the upper two feet of this profile is exceedingly high, decreasing from 635 p.p.m. in the zero to six-inch layer to 200 p.p.m. in the 18 to 24-inch layer. From this point downward, although the concentration drops off rapidly, it is still substantial even four feet below the surface. The distribution pattern is shown graphically in Figure 5.

No other soil of this family was examined. Accordingly, the degree to which this specimen is representative of the family is not known. It seems probable that such large amounts of available phosphorus as were found in this profile would occur naturally only under conditions of relatively low rainfall, as in the present instance. It may be noted in this connection that recent analyses of other Hamakua Coast soils, similarly derived from volcanic ash, with approximately the same conditions of rainfall, but at the much greater elevations of 5000 to 6000 feet, have shown comparable amounts of available phosphorus. Other soils excessively high in phosphorus and also derived from volcanic ash under moderate rainfalls were encountered in the cane lands of the Kau region. These will be considered later.

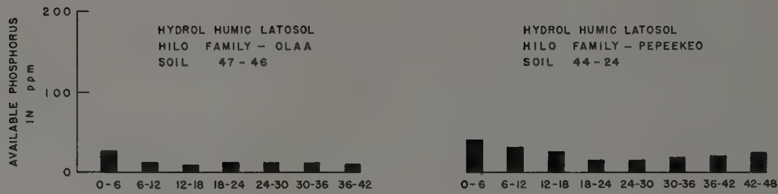


Figure 7

Figure 8

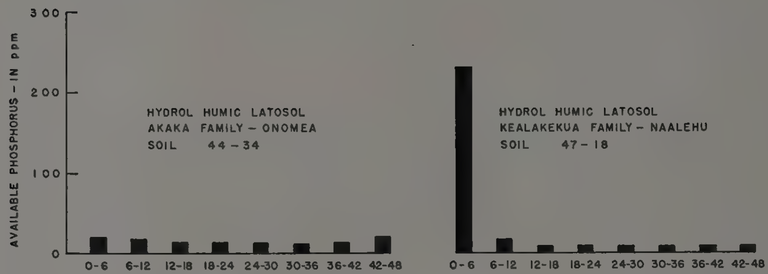


Figure 9

Figure 10

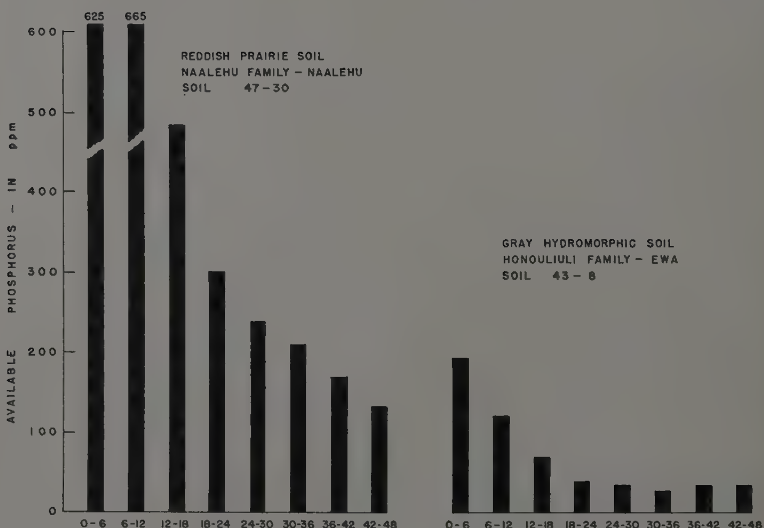


Figure 11

Figure 12

In the Ookala family of this group of soils, three profiles were studied. The distribution of phosphorus in one of these, at Laupahoehoe, is shown graphically in Figure 6. These soils have originated under rainfalls approximately double that under which the Paauhau soil was formed. Here are no excessive amounts of available phosphorus. The surface layer of one of the soils at Hamakua contains more phosphorus than the corresponding subsoil, but in the other two there is little differentiation. Phosphorus in the Hakalau profile is substantially below the critical level for sugar cane.

HYDROL HUMIC LATOSOLS

The Hydrol Humic Latosols are the soils of the humid regions. They include the sugar cane lands of the Puna district and of the Hilo Coast as far north as Hakalau. From Hakalau to the drier end of the Hilo Coast, they are found in the wetter, mauka areas.

Of the soils in the Hilo family, five were studied. The distribution of phosphorus in the profiles of these soils is similar to that in the Ookala soils. Below the surface six or 12 inches, phosphorus is rather uniformly distributed and is generally very low. Examples of this pattern may be seen in Figure 7 which represents a soil at Olaa and in Figure 8 which represents a soil at Pepeekeo. Supplies of phosphorus in two of the soils are below the critical level.

Five soils of the Akaka family were examined. The more mauka sugar cane lands of the Hilo Coast are made up of soils of this family. So far as the cultivation of sugar cane is concerned, rainfall is at a maximum, attaining mean annual values in excess of 200 inches. Of the five soils examined, three are in sugar cane while two represent adjacent forested soils.

Phosphorus is below the critical level in all but one of the soils. Phosphorus is slightly higher in the surface foot of two of the sugar cane soils than in corresponding subsoils, and it is much higher in that of the third. In no instance does the level of phosphorus exceed 20 p.p.m. at any point below the depth of 12 inches. In the forested soils, phosphorus is not in excess of this value anywhere in the profile. The horizonal distribution of phosphorus in one of the Akaka sugar cane soils at Onomea is illustrated in Figure 9.

The third and final member of the Hydrol Humic Latosols is the Kealakekua family. This soil is found in mauka areas in the Kau region, where it is cropped to cane.

Distribution of phosphorus in the profile of the single soil studied (Figure 10) follows a most unusual pattern. Phosphorus is in very high concentration (228 p.p.m.) in the zero to 6-inch layer. In the 6 to 12-inch layer, it drops abruptly to the value of 14 p.p.m. Below this level it is constant at 6 p.p.m.

The volcanic ash which gives rise to the surface layer of the Kealakekua family of soils appears to have been laid down in thin deposits over old, weathered lavas. Since these deposits are relatively young and since the rainfall is moderate, it is not surprising to find in this zone a high content of available phosphorus. Nor is it surprising to encounter low levels of phosphorus in the older subsurface horizons. In this region of the profile, however, one would hardly expect to find such sharp division between the zones containing excessive amounts of phosphorus and those deficient in phosphorus. It must be inferred from this differentiation either that the surface soil has suffered severe recent erosion, or that cultural operations have resulted in amazingly little mixing of the surface-foot of soil.

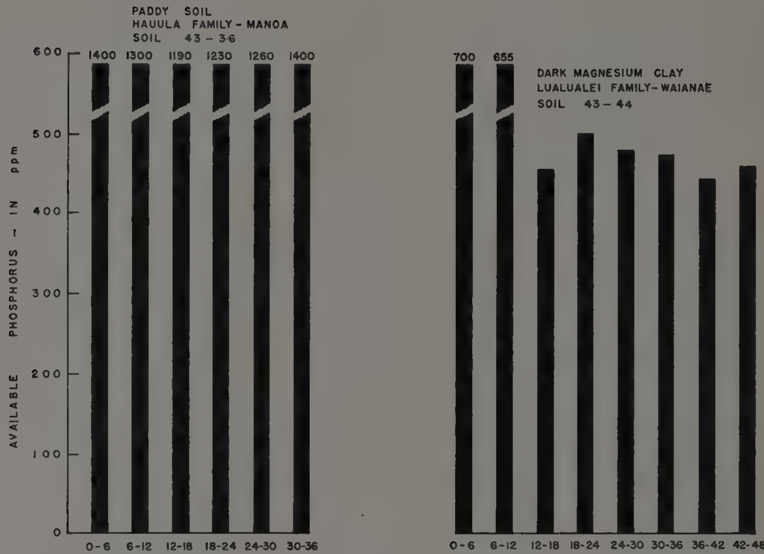


Figure 13 DEPTH IN INCHES **Figure 14**

REDDISH PRAIRIE SOILS

Soils of the Reddish Prairie Group are planted to sugar cane at Pahala and Naalehu only. The single Prairie soil examined is of the Naalehu family. The distribution of phosphorus in its profile is illustrated in Figure 11.

The entire profile is exceedingly high in available phosphorus, the range being from 665 p.p.m. in the 6 to 12-inch layer to 130 p.p.m. in the 42 to 48-inch layer. The surface six inches contained 625 p.p.m. of the element.

The Prairie soils are derived from young volcanic ash under conditions of relatively low rainfall, and are, therefore, only slightly weathered. In the soil studied, the reaction below the surface layer is neutral (cf. Appendix). These conditions appear to account for the unusually high phosphorus content of the soil.

GRAY HYDROMORPHIC SOILS

Consideration may now be given to one of the Gray Hydromorphic soils, a member of the Honouliuli family, which is exemplified by the flat, heavy, slow-draining soils of the Ewa plain from which samples were taken for study. The relationship between available phosphorus and depth of soil is illustrated in Figure 12.

The supply of phosphorus approaches the high value of 200 p.p.m. in the surface six inches, then it decreases proportionately with depth for 18 to 24 inches. From this point to the bottom of the profile, it is practically constant at about 35 p.p.m.

PADDY SOILS

As the name suggests, Paddy soils either are, or have been, planted to rice or taro. There is but one family, the Hauula family. The particular profile examined was in an area of Manoa Valley which has been devoted in recent years to the culti-

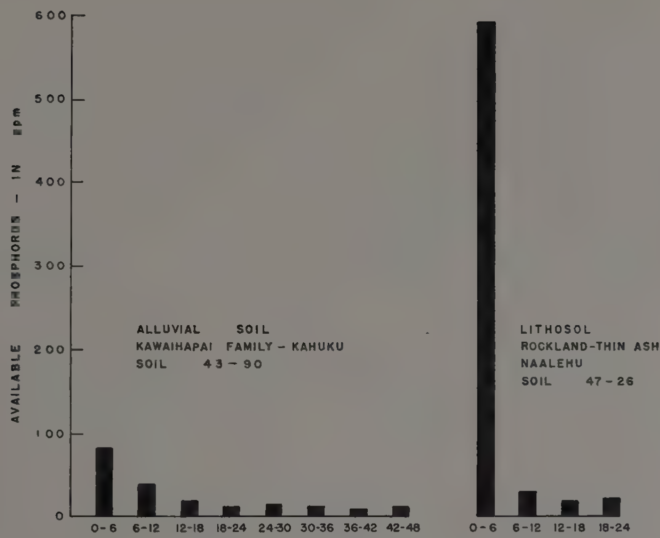


Figure 15 Figure 16

vation of Napier grass. Soil samples were secured to a depth of only three feet. The vertical distribution of phosphorus in this soil is shown graphically in Figure 13.

The entire profile is unbelievably and uniformly high in available phosphorus. Phosphorus at the depth of three feet is as high as in the surface six inches. Values range from 1190 to 1400 p.p.m.

The reason for the immoderate quantities of phosphorus in this soil is not overly apparent. Undoubtedly, moderate weathering resulting from poor drainage is a factor.

DARK MAGNESIUM CLAYS

Substantial areas of Dark Magnesium Clays, a family of heavy, plastic clay soils, are planted to sugar cane on the islands of Oahu and Kauai. The Lualualei family is the only member of the Group recognized in Hawaii. The one soil studied is in the Waianae Valley of Oahu.[4]

Excessive amounts of phosphorus are present in all portions of the profile (Figure 14). The over-all range is from 445 to 700 p.p.m., the latter value representing the surface six inches. As in the case of the Paddy soil, the high amounts of phosphorus are associated with poor drainage.

ALLUVIAL SOILS

Sugar cane is grown on only one of the two soil families of the Alluvial Soils Group, namely, the Kawaihapai family. This is the alluvium of the drier regions.

Phosphorus is in good supply in the surface foot of the Kahuku profile studied. Below the one-foot level, values are consistently very low. See Figure 15.

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[4] The phosphorus analysis of this soil may not be strictly comparable to analyses of other soils studied owing to the presence of small amounts of calcareous material. (The pH range for the profile is 7.3 to 7.5). The effect of carbonates, however, is partly nullified by the low soil to solution ratio employed.

LITHOSOLS

Finally, the distribution of phosphorus in the profile of a shallow Rockland member of the Lithosol group of soils at Naalehu was studied. Here again there is a surface layer, derived from young ash under relatively low rainfall. Here again a tremendously high concentration of available phosphorus is found in the surface layer. As may be seen by reference either to the Appendix or to Figure 16, differentiation with respect to phosphorus content between the zero to 6 and 6 to 12-inch layers of soil is most abrupt. Phosphorus drops from 590 p.p.m. in the first layer to 28 p.p.m. in the second. A parallel situation was noted in the profile of the Hydrol Humic Latosol from the same region.

DISCUSSION

The supply of available phosphorus in Hawaiian soils, apart from that resulting from fertilization, appears to be largely a function of the degree of weathering. Of the soils examined, those high in available phosphorus fall into two categories: either they are young soils formed under moderate rainfall, or they are soils formed under conditions of impeded drainage. In either case they are only moderately weathered. The soils naturally low in available phosphorus are the more weathered soils which have developed under good drainage.

As soils weather, bases are liberated and leached from the soil. Much of the weathering in the tropics involves the loss of silica also, with a resultant concentration of hydrated oxides of iron and aluminum. These oxides possess strong affinities for phosphorus and tend to fix this element in unavailable forms. Therefore, in the more weathered Hawaiian soils, it is not surprising to find only small amounts of phosphorus which are utilizable by plants, even though the soils are well supplied with total phosphorus (7).

In the slightly weathered soils, on the other hand, not only are iron and aluminum less concentrated, but more of the bases are present. Under these conditions, a larger proportion of the phosphorus is held in forms which plants can use.

The true picture is undoubtedly more complex than the foregoing outline indicates. It is helpful, however, in explaining the great differences in supplies of available phosphorus in Island soils.

All the soils studied, except those from areas of grass and forest, have been in sugar cane for a great many years. The majority have received phosphate fertilizer with each crop. It may be of interest, therefore, to consider the fate of the added phosphorus. In so doing, the relatively few less-weathered soils containing abnormally large quantities of the element will be ignored.

With many of the profiles, levels of available phosphorus are clearly at a maximum in the surface layer. These higher levels may have resulted to some extent from the deposition of organic residues upon the surface either before or after the soils were placed under cultivation. The effect of this material, however, is probably slight, owing to the resistance of organic phosphates to microbial attack. Certainly available phosphorus is not consistently highest in the surface layers of the virgin soils examined. The observed differentials appear, therefore, to be primarily attributable to fertilization.

Although comfortable reserves of available phosphorus have accumulated in many of the soils, they are absent in others. In some of the latter, phosphorus is still

below the critical level for sugar cane. Such soils, so far as the present study indicates, are restricted to the Humic and Hydrol Humic Latosols.

There are several possible explanations for the apparent lack of residual phosphorus in these soils. Among them are the following:

1. The amount of phosphate applied as fertilizer has been very moderate, on the average not in excess of 50 pounds P_2O_5 per acre per crop. It is doubtful if this exceeds the rate at which the nutrient has been removed from the soil by cropping, even when non-millable tops and trash have remained in the field. According to the Handbook of Hawaiian Soils (7), 75 tons of millable cane contain about 45 pounds of P_2O_5.[5]

2. Applied phosphorus is retained principally in the surface layer. When conditions foster erosion, it is this surface soil that is lost, carrying the phosphorus with it. Moreover, it is the finer soil particles that are most active in holding phosphorus, and it is these finer particles which are most subject to the forces of erosion.

3. The Humic and Hydrol Humic Latosols have tremendous capacities for fixing phosphorus (2). Davis (6) has shown that this fixation may take place in fairly acid solution. It is possible, therefore, that part of the phosphate which is added to the soil and subsequently fixed, is not subject to extraction by the dilute acid employed in the study.

The profiles from the two Hilo Coast forest soils contain amounts of phosphorus which are very low. By sugar cane standards, both soils are deficient in this nutrient. This suggests that the natural status of available phosphorus in the soils of this region is inadequate to meet the requirements of the cane crop. Therefore, when these soils are employed in the production of sugar, it becomes necessary to supplement the native supply of the element by fertilization.

Levels of available phosphorus in subsoils have apparently been raised very little by fertilization. Supplies of phosphorus below the surface 12 inches remain extremely low in numerous profiles of the Low Humic, Humic and Hydrol Humic Latosols. Values of less than 10 p.p.m. are common. The question naturally arises as to the advisability of ignoring such deficiencies.

In the cultivation of some crops, phosphorus-deficient subsoils are treated directly with phosphate fertilizer. The presence of an adequate supply of this nutrient in the subsoil is credited with stimulation of root development. This treatment is believed to be particularly beneficial in inadequately aerated subsoils where root development tends to be retarded. Such a condition is common in many of the humid region soils of the Islands.

Severe erosion, particularly in recent years, has carried away substantial quantities of the surface layers of the Humic and Hydrol Humic Latosols in parts of the Hilo and Hamakua Coasts. Subsequent plowing operations have resulted in tilled layers containing considerable admixtures of phosphorus-deficient subsoil. The status of available phosphorus in these mixed layers warrants careful consideration.

[5] With current removal from the field of non-millable portions of the crop, losses of phosphorus are correspondingly greater.

SUMMARY

By a modification of the Truog procedure, a study was made of the distribution of available phosphorus in 31 soil profiles of the islands of Oahu and Hawaii. The results may be summarized as follows:

The supply of available phosphorus was found to be related to the degree of weathering of the soil. Well-weathered soils contain relatively small amounts of available phosphorus. Soils which are only moderately weathered, whether due to their youthful nature or to impeded drainage, tend to be high in available phosphorus. In the surface soils under study, the over-all range of phosphorus content is from 8 to 1350 p.p.m.

Fertilization has resulted in the accumulation of considerable reserves of available phosphorus in surface layers of many of the soils examined. This is not generally true, however, of the Humic and Hydrol Humic Latosols. In some of these soils, the supply of available phosphorus is below the critical level for the optimum growth of sugar cane.

Levels of available phosphorus in the subsoils of some of the Low Humic, Humic and Hydrol Humic Latosols are exceedingly low. The significance of this observation in relation to the cultivation of cane on soils with shallow surface layers is discussed.

The amounts and distribution of available phosphorus in the profile may differ considerably not only within a given Great Soil Group but even within the Soil Family.

With the majority of profiles, levels of available phosphorus diminish with depth.

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APPENDIX

Distribution of Available Phosphorus in Soil Profiles

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
43–34a	Ewa	350	20	Low Humic Latosols	Molokai	N1	Cactus, Grass	0– 6	25	5.6
34b								6–12	19	6.3
34c								12–18	24	6.8
34d								18–24	18	6.7
34e								24–30	19	6.7
34f								30–36	18	6.6
34g								36–42	25	6.3
34h								42–48	22	6.3
43–48a	Waipahu	200	20	Low Humic Latosols	Molokai	N1	Sugar cane	0– 6	58	6.5
48b								6–12	29	6.7
48c								12–18	10	7.0
48d								18–24	9	7.1
48e								24–30	9	7.0
48f								30–36	7	7.0
48g								36–42	6	6.9
48h								42–48	8	6.9
43–69a	Waialua	350	45	Low Humic Latosols	Lahaina	N2	Sugar cane	0– 6	71	5.8
69b								6–12	38	6.1
69c								12–18	19	6.2
69d								18–24	8	6.2
69e								24–30	9	6.2
69f								30–36	7	6.2
69g								36–42	8	6.2
69h								42–48	7	6.2
43–16a	Poamoho	700	45	Low Humic Latosols	Wahiawa	N3	Napier grass	0– 6	30	6.6
16b								6–12	24	6.7
16c								12–18	10	6.6
16d								18–24	5	6.6
16e								24–30	6	6.8
16f								30–36	5	6.9
16g								36–42	10	6.9
16h								42–48	9	6.8

Distribution of Available Phosphorus in Soil Profiles (Continued)

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
44–22a	Kohala................	150	40	Low Humic Latosols	Kohala	N5	Sugar cane	0– 6	257	6.1
22b								6–12	79	6.5
22c								12–18	29	6.9
22d								18–24	28	6.8
22e								24–30	26	6.8
22f								30–36	26	6.7
22g								36–42	36	6.8
22h								42–48	45	6.9
44–23a	Kohala................	600	50	Low Humic Latosols	Kohala	N5	Sugar Cane	0– 6	45	5.3
23b								6–12	43	5.3
23c								12–18	47	5.3
23d								18–24	68	5.7
23e								24–30	64	5.8
23f								30–36	77	5.8
23g								36–42	80	5.7
23h								42–48	100	5.9
44–20a	Kohala................	250	60	Low Humic Latosols	Kohala	N5	Sugar cane	0– 6	39	5.0
20b								6–12	42	5.5
20c								12–18	33	5.8
20d								18–24	38	5.8
20e								24–30	51	5.5
20f								30–36	61	5.1
20g								36–42	33	5.1
20h								42–48	44	5.0
44–21a	Kohala................	1200	70	Low Humic Latosols	Kohala	N5	Sugar cane	0– 6	58	5.7
21b								6–12	47	5.8
21c								12–18	25	6.0
21d								18–24	26	6.2
21e								24–30	26	6.3
21f								30–36	31	6.5
21g								36–42	42	6.5
21h								42–48	54	6.6
44–18a	Kohala................	900	90	Low Humic Latosols	Kohala	N5	Sugar cane	0– 6	45	5.3
18b								6–12	44	5.2
18c								12–18	44	5.4
18d								18–24	43	5.4
18e								24–30	70	5.4

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
44–19a	Kohala	950	90	Low Humic Latosols	Kohala	N5	Sugar cane	0–6	105	5.5
19b								6–12	25	5.8
19c								12–18	28	5.8
19d								18–24	35	5.9
19e								24–30	26	5.9
19f								30–36	37	5.9
19g								36–42	51	5.9
19h								42–48	60	5.9
44–26a	Paauhau	400	65	Humic Latosols	Paauhau	A4	Sugar cane	0–6	635	5.9
26b								6–12	565	6.0
26c								12–18	255	5.9
26d								18–24	200	6.1
26e								24–30	87	6.3
26f								30–36	53	6.3
26g								36–42	40	6.4
26h								42–48	40	6.5
44–27a	Hamakua	1250	120	Humic Latosols	Ookala	A5	Sugar cane	0–6	41	5.3
27b								6–12	26	5.2
27c								12–18	14	5.4
27d								18–24	21	5.4
27e								24–30	10	5.4
27f								30–36	11	5.5
27g								36–42	14	5.5
27h								42–48	18	5.7
44–30a	Laupahoehoe	600	125	Humic Latosols	Ookala	A5	Sugar cane	0–6	26	4.7
30b								6–12	28	4.6
30c								12–18	30	4.7
30d								18–24	19	5.4
30e								24–30	18	5.5
30f								30–36	23	5.6
30g								36–42	18	5.4
30h								42–48	16	5.3
44–31a	Hakalau	300	145	Humic Latosols	Ookala	A5	Sugar cane	0–6	16	5.1
31b								6–12	14	5.3
31c								12–18	9	5.4
31d								18–24	12	5.4
31e								24–30	11	5.4
31f								30–36	11	5.4
31g								36–42	12	5.5
31h								42–48	13	5.5

Distribution of Available Phosphorus in Soil Profiles (Continued)

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
47–46a	Olaa	250	140	Hydrol Humic Latosols	Hilo	K6	Sugar cane	0–6	24	5.7
46b								6–12	9	6.1
46c								12–18	8	6.3
46d								18–24	9	6.2
46e								24–30	10	6.2
46f								30–36	10	6.1
46g								36–42	8	6.2
44–24a	Pepeekeo	600	150	Hydrol Humic Latosols	Hilo	K6	Sugar cane	0–6	39	4.8
24b								6–12	30	4.9
24c								12–18	23	4.9
24d								18–24	13	5.0
24e								24–30	13	5.2
24f								30–36	18	5.5
24g								36–42	20	5.6
24h								42–48	23	5.6
47–38a	Olaa	650	150	Hydrol Humic Latosols	Hilo	K6	Sugar cane	0–6	17	5.7
38b								6–12	8	6.0
38c								12–18	8	6.1
38d								18–24	9	5.9
38e								24–30	11	6.1
38f								30–36	11	6.1
38g								36–42	9	6.0
38h								42–48	9	6.0
44–35a	Onomea	1000	180	Hydrol Humic Latosols	Hilo	K6	Sugar cane	0–6	44	5.1
35b								6–12	42	5.4
35c								12–18	29	5.6
35d								18–24	27	5.8
35e								24–30	26	5.8
35f								30–36	23	5.8
35g								36–42	24	5.8
35h								42–48	24	5.8
47–53a	Olaa	1600	200	Hydrol Humic Latosols	Hilo	K6	Sugar cane	0–6	41	5.6
53b								6–12	24	5.9
53c								12–18	23	6.2
53d								18–24	26	6.2
53e								24–30	20	6.2
53f								30–36	15	6.3
53g								36–42	17	6.3
53h								42–48	15	6.3

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
44–28a	Laupahoehoe..........	1500	150	Hydrol	Akaka	K8	Sugar	0– 6	25	5.0
28b				Humic			cane	6–12	9	5.4
28c				Latosols				12–18	5	5.4
28d								18–24	15	5.4
28e								24–30	9	5.4
28f								30–36	8	5.4
28g								36–42	8	5.4
28h								42–48	5	5.3
44–34a	Onomea...............	1500	215	Hydrol	Akaka	K8	Sugar	0– 6	19	4.9
34b				Humic			cane	6–12	17	5.2
34c				Latosols				12–18	13	5.4
34d								18–24	13	5.7
34e								24–30	13	5.6
34f								30–36	12	5.7
34g								36–42	14	5.7
34h								42–48	20	5.5
44–33a	Onomea...............	1600	215	Hydrol	Akaka	K8	Forest	0– 6	10	4.8
33b				Humic				6–12	5	5.0
33c				Latosols				12–18	5	5.3
33d								18–24	5	5.4
33e								24–30	5	5.6
33f								30–36	5	5.4
33g								36–42	5	5.3
33h								42–48	5	5.5
44–32a	Pepeekeo..............	1400	230	Hydrol	Akaka	K8	Sugar	0– 6	32	5.2
32b				Humic			cane	6–12	41	5.2
32c				Latosols				12–18	7	5.6
32d								18–24	6	5.5
32e								24–30	6	5.5
32f								30–36	13	5.6
32g								36–42	19	5.7
32h								42–48	10	5.5
44–25a	Pepeekeo..............	2000	240	Hydrol	Akaka	K8	Forest	0– 6	8	4.4
25b				Humic				6–12	11	4.9
25c				Latosols				12–18	18	5.3
25d								18–24	20	5.4
25e								24–30	12	5.2
25f								30–36	8	5.3
25g								36–42	8	5.5
25h								42–48	7	5.4

Distribution of Available Phosphorus in Soil Profiles (Continued)

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
47-18a	Naalehu..............	2500	80	Hydrol	Kealakekua	K10	Sugar	0- 6	228	5.6
18b				Humic			cane	6-12	14	5.9
18c				Latosols				12-18	6	6.0
18d								18-24	6	6.1
18e								24-30	6	6.2
18f								30-36	6	6.2
18g								36-42	6	6.1
18h								42-48	6	6.0
47-30a	Naalehu..............	500	55	Reddish	Naalehu	C3	Sugar	0- 6	625	6.3
30b				Prairie			cane	6-12	665	6.7
30c				Soils				12-18	485	6.9
30d								18-24	300	7.1
30e								24-30	238	7.0
30f								30-36	212	7.0
30g								36-42	167	7.0
30h								42-48	130	7.0
43-8a	Ewa..................	25	20	Gray	Honouliuli	H1	Sugar	0- 6	193	7.1
8b				Hydro-			cane	6-12	120	7.2
8c				morphic				12-18	68	7.3
8d				Soils				18-24	36	7.3
8e								24-30	34	7.2
8f								30-36	27	7.2
8g								36-42	35	6.9
8h								42-48	36	6.8
43-36a	Manoa................	150	40	Paddy	Hauula	P	Napier	0- 6	1400	6.3
36b				Soils			grass	6-12	1300	6.4
36c								12-18	1190	6.4
36d								18-24	1230	6.4
36e								24-30	1260	6.6
36f								30-36	1400	6.6

Soil No.	Location	Elevation Feet	Rainfall Inches	Great Soil Group	Soil Family	Symbol	Vegetation	Depth Inches	Phosphorus p.p.m.	pH
43–44a	Waianae.............	50	20	Dark Magnesium Clays	Lualualei	M	Sugar cane	0– 6	700	7.5
44b								6–12	665	7.4
44c								12–18	465	7.4
44d								18–24	500	7.4
44e								24–30	480	7.4
44f								30–36	475	7.3
44g								36–42	445	7.3
44h								42–48	460	7.3
43–90a	Kahuku..............	25	35	Alluvial Soils	Kawaihapai	Vt	Sugar cane	0– 6	82	5.0
90b								6–12	36	5.0
90c								12–18	16	4.9
90d								18–24	11	5.0
90e								24–30	12	4.9
90f								30–36	11	4.9
90g								36–42	7	4.9
90h								42–48	10	4.8
47–26a	Naalehu..............	1200	55	Lithosols	Rockland, thin ash	L2A	Sugar cane	0– 6	590	6.1
26b								6–12	28	6.2
26c								12–18	19	6.3
26d								18–24	20	6.6

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